Recent OSS Radiative Transfer Model Improvements and Application to Sounding

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EDR Algorithm Development and Instrument Design Testing Environments:

- Develop system with dual tasks in mind
  - •Advance the state of Atmospheric and surface parameter retrieval algorithms
  - •State of the art forward models
    - •Both LBL and Fast model
  - •Aid in the development and testing of new instrument designs
- Modularized software developed which allows for transparent updates/changes in retrieval algorithms and forward model development
- Can either simulate observations or ingest "real" measurement data
- **Optimal Spectral Sampling(OSS)** fast radiative transfer model primary RT model
  - •Modular design does not limit testing other RT models including line-by-line(LBL)
- Examples of recent trade studies/algorithm development efforts
  - •OSS comparison with OPTRAN with the JCDA: AIRS ILS
  - •OSS validation studies using AIRS data
  - •Testing retrieval algorithms with AIRS:
    - •Both land and ocean environments
    - •Temperature and Water vapor retrieval
    - •Surface emissivity
    - •Cloud property retrievals
  - •HES instrument design trades
- **Development efforts centered around**
  - •**Unified Retrieval(UR)** algorithm/infrastructure
  - •**OSS** development/implementation

AER's Unified Retrieval (UR) Physical Algorithm Concept:

- Concept is to retrieve state parameters simultaneously with the ability to incorporate several data sources into the retrieval stream
- Initially applied and tested with DMSP Block 5D3 sensor suite
- Is the basis for the **NPOESS CrIMSS** and **CMIS** EDR algorithms. ATBD's available from the IPO (not most recent revisions)
  - •**http://140.90.86.6/IPOarchive/SCI/atbd/ATBD_V.02CorePhysicalInversionModule.pdf**
  - •**http://140.90.86.6/IPOarchive/SCI/atbd/cris_atbd_03_09_01.pdf**
- Incorporates state of the art **OSS** fast radiative transfer model
- Tested on recent Satellite/Aircraft based instruments
  - •AMSU •SSMI •AMSR
  - •AIRS •NAST-I

Optimal Spectral Sampling(OSS)

•OSS absorption parameterization leads to ***fast*** and ***numerically accurate*** RT modeling:

•OSS-based RT model can approach line-by-line calculations arbitrarily closely
- ***Adjustable numerical accuracy***:
  - – Possibility of trade off between accuracy and speed

•Unsupervised training
- ***No empirical adjustment:***

•Provides flexible handling of (variable) trace molecular species
- ***Designed to handle large number of variable trace species*** w/o any change to model – low impact on computational cost
- Selection of variable trace gases at run time

•Memory requirements do not change whether we are dealing with one or more instruments
- Execution speed primarily driven by total spectral coverage and maximum spectral resolution (not by number of instruments)

•***Accurate handling of multiple scattering*** (cloudy radiance assimilation)
- ***OSS-SCAT***

•Used in:
- ***NPOESS/ CrIS, CMIS and OMPS (IR) retrieval algorithms***
- ***JCSDA CRTM***

•Beta version of OSS-based CRTM about to be tested at NCEP (Garand et al. 2001),

•Recent ITSC AIRS comparison (Saunders et al., 2005)

•Currently working on integrating into ***MODTRAN*** (AFRL-sponsored effort)

•NASA's Mars Fundamental Research Program: OSS forward model has been developed for the Thermal Emission Spectrometer (TES) onboard the Mars Global Surveyor spacecraft (Christensen et al. 2001).

OSS tables in use for many instrument designs

- Microwave:
  - AMSU(NOAA and EOS) •AMSR
  - SSMI, SSMI/S •ATMS(NPOESS,NPP)
  - CMIS(NPOESS)
- IR:
  - CrIS(NPOESS,NPP) •AIRS
  - NASTI(Airborne) •HES(PORD)

Optimal Spectral Sampling (OSS) Method:

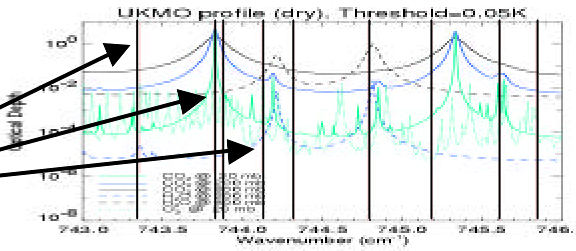
- OSS fast forward model
  - •Channel radiance for inhomogeneous atmospheric path represented by weighted sum over specific frequencies or “nodes”

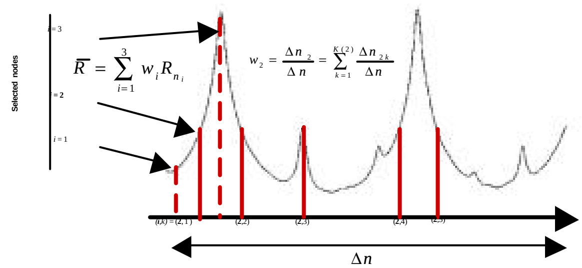
$$\overline{R} = \int_{\Delta n} f(n)R(n)dn \cong \sum_{i=1}^{N} w_i R(n_i); \qquad ?_i \in \Delta n$$

  - •Automated search for smallest subset of **nodes** and weights for which the error is less than a prescribed tolerance

$$\left\{(n_i, w_i) \;\; i = 1,.., N\right\} \qquad e_N = \sum_s \left[R^s - \sum_{i=1}^{N} w_i R^s_{n_i}\right]^2$$

  - •In the training, radiances calculated with a line-by-line model (e.g. LBLRTM, GENLN) using a globally representative ensemble of atmospheres, surface conditions, viewing angles, etc..
  - •Radiance training fast
    - •Planck function accounted for exactly



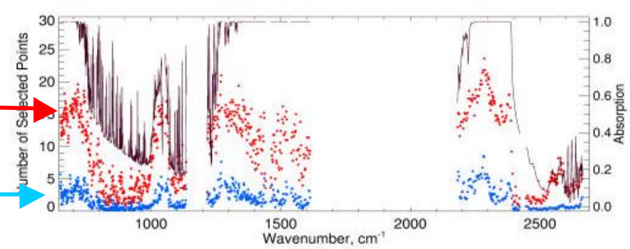


Localized versus Generalized Training

•***Localized training*** (benchmark) operates on individual channels, one at a time – node redundancy due to overlapping ILS

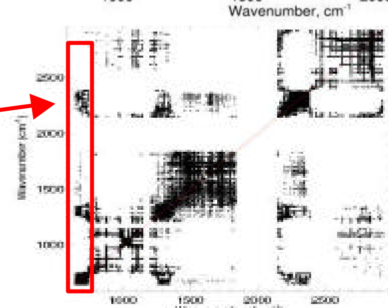
•AIRS (2378 channels):

- **Average # nodes per channel: ~9 nodes/channel**
- **Total number of nodes/number of channel (i.e. no redundancy) = 1.9 nodes/channel**



•***Generalized Training*** operates on groups of *N* channels (up to full channel set)

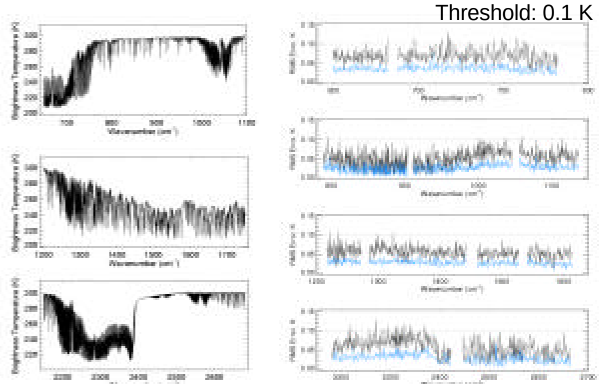
- Exploits node-to-node correlation to minimize total number of nodes across a spectral domain
- Results in significant increase in number of points in any given channel



Radiance Correlation

OSS Applied to the AIRS ILS

Threshold: 0.1 K

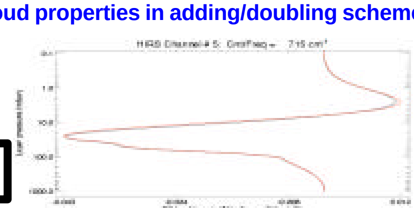


Threshold: 0.05K

- •Training performed with 260 profiles
- •Validation performed using 52 independent profiles
- •Both sets obtained from ECMWF
- •Errors for two tolerance values, 0.1K and 0.05K

Jacobians

- **Required for retrievals/assimilations**
- **Calculated at little added computational cost**
  - **•Simultaneous with radiance**
- **Analytic Jacobians, not finite diff.**
  - **•Temperature**
  - **•All variable gases**
  - **•Surface properties**
  - **•Future: Cloud properties in adding/doubling scheme**

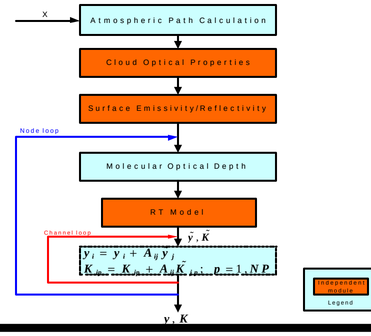


O_3 Jacobian for 715cm[1]

OSS Forward Model

RTM structure

- Main loop is the node loop
  - **Internal channel loop to update channel radiance and Jacobians**
  - **Similar structure adopted for CRTM**
- LUT of *kabs* stored for all relevant molecules as a function of temperature
  - **Self broadening included for water vapor**
  - **Maximum brightness temperature error with current LUT < 0.05K in infrared and <~0.01K in microwave**
- Use simple monochromatic RT model (clear or scattering)
  - **Jacobians (required for retrieval applications) are straightforward in the clear-sky (e.g. CrIS ATBD)**

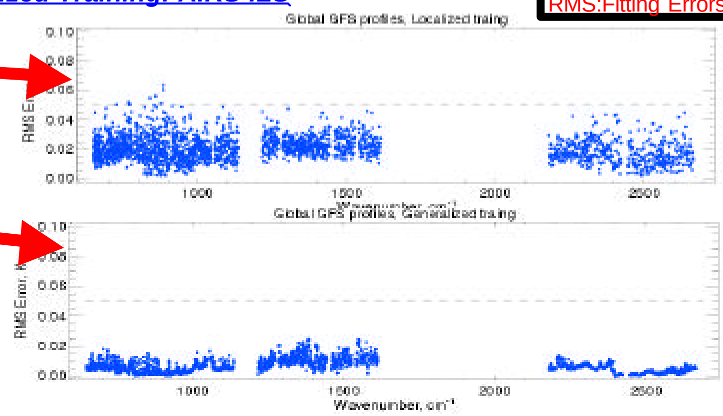


OSS Generalized Training: AIRS ILS

RMS:Fitting Errors

- Localized training (0.05K accuracy):
  ~2nodes /channel
  ~5000 monochromatic calculations for full AIRS channel set
- Generalized training:
  ~0.1 node/channel
  Reduces number of monochromatic calculations to ~250

Speed gain ~ 20 compared to localized training for AIRS



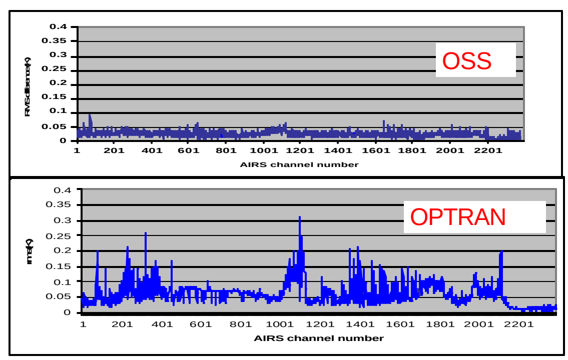
OSS in JCSDA CRTM: Comparison with OPTRAN

- OSS compared with OPTRAN, AIRS ILS
  - Timing
  - Accuracy

Timings based upon 48 profiles, 7 angles(336 total)

	OPTRAN-V7 Forward, Jacobian + Forward	OPTRAN-comp Forward, Jacobian + Forward	OSS Jacobian + Forward
AIRS	7m20s, 22m36s	10m33s, 35m12s	3m10s
HIRS	4s, 13s	5s, 17s	9s

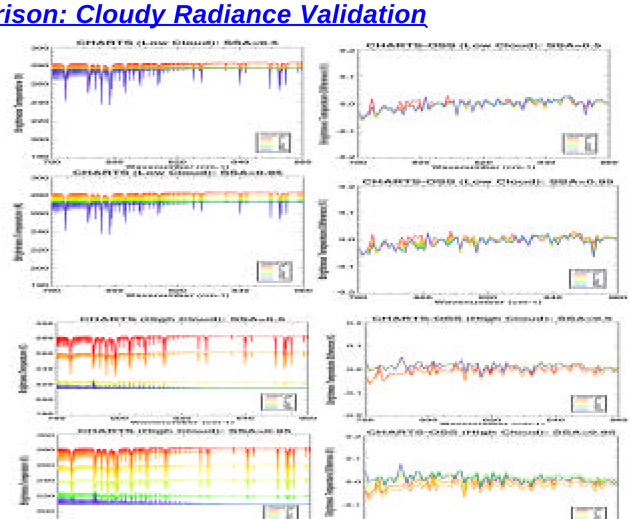
- OSS incorporated into CRTM
  - Both MW and IR will be available



Comparison with LBL calculations
Radiance residual RMS

OSS-SCAT/CHARTS Comparison: Cloudy Radiance Validation

- CHARTS(Moncet and Clough, 1997)
  - Fast adding-doubling scheme for use with LBLRTM
  - Uses tables of layer reflection/transmission as a function of absorption computed at runtime
- OSS-SCAT:
  - Single wavelength version of CHARTS (no spectral interpolation)
- Cloudy validation:
  - Molecular absorption from 740-900 cm^{-1} domain
  - 1cm^{-1} boxcars, thermal only
  - Cloud extinction OD range: 0-100
- Example:
  - 780-860 cm^{-1}
  - Low cloud case (925-825 mb)
  - High cloud case (300-200 mb)

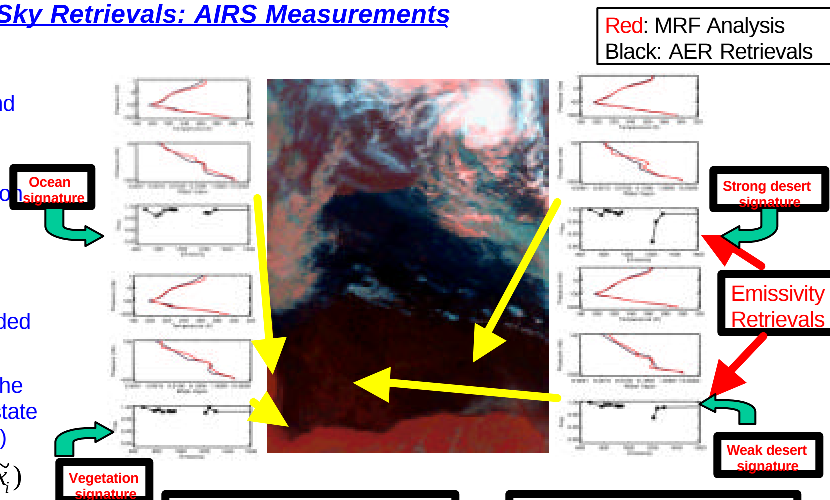


Clear Sky Retrievals: AIRS Measurements

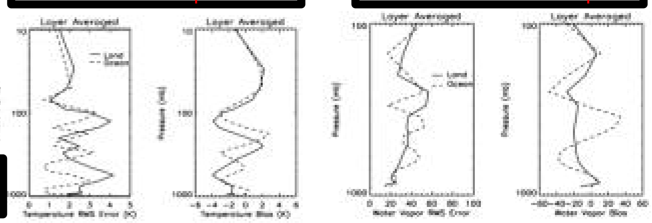
- Non-linear iterative physical retrieval method with radiometric and geophysical constraints
- Simultaneous retrieval of required atmospheric and surface parameters. Well suited for modern high resolution hyper-spectral instruments
- Empirical Orthogonal Function (EOF) decomposition of retrieval parameters
  - •Reduce the dimensionality of the inversion problem.
  - •Stabilizes inversion and reduces the time needed per retrieval.
- Within this framework: basic quantity retrieved is the difference between state vector and background state vector in reduced dimension space(Rodgers 1976)

$$\Delta\tilde{x}_{i+1} = (\tilde{K}_i^T S_y^{-1}\tilde{K}_i + \Lambda^{-1})^{-1}\tilde{K}_i^T S_y^{-1}(y_0 - y_i + \tilde{K}_i\Delta\tilde{x}_i)$$

- Parameters retrieved
  - •Temerature/water vapor profiles
  - •Skin temperature
  - •Surface Emissivity(12 hinge points)
  - •Ozone scaling factor
- Retrievals performed on each FOV
  - •No cloud clearing nor MW first guess
  - •Climatologic first guess/background

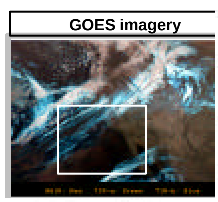


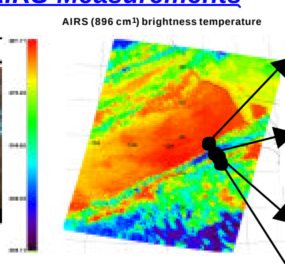
Statistics determined Using only MODIS Determined Clear pixels

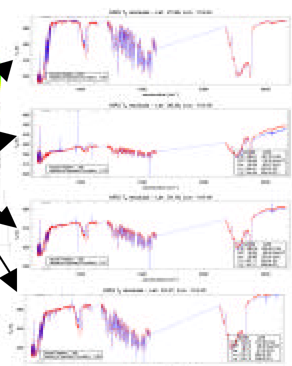


Cloud Property Retrievals: AIRS Measurements

- Single FOV cloud parameter retrievals
- Fix Atmosphere and surface
  - • profiles and SST from NCEP/GDAS
- Retrieved cloud parameters
  - •Cloud top/thickness
  - •Ice particle effective diameter
  - •Ice water Path(IWP)
  - •Effective temperature
- MODIS based retrievals used for first guess
  - •AER SERCAA cloud algorithms
- RTM:
  - •OSS-SCAT(100 layers)
  - •4 stream



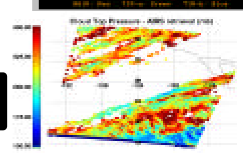




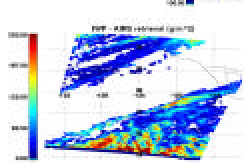
Radiances: Calculated Vs Observed

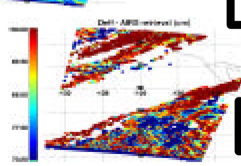
Radiances calculated with OSS-SCAT

Cloud Top Pressure



IWP





Effective diameter

Retrievals In Node Space:Generalized OSS

Retrievals based upon 500 NOAA88 profiles

•Variational retrieval methods:
- Average channel uses ~150 nodes
- Mapping Jacobians from node to channel space partially offsets speed gain

$$d x_{n+1} = \left(K_n^T S_e^{-1} K_n + S_x^{-1}\right) K_n^T S_e^{-1}\left[\left(y_n - y^m\right) + K_n d x_n\right],$$

where,

$y = A\,\tilde{y}$ and

$K = A\,\tilde{K}$

•Alternative:
- Operate directly in node space

$$y^m = A\,\tilde{y}^m \rightarrow \hat{\tilde{y}}^m = H\,y^m$$

- Avoids Jacobians transformation all together and reduce K-matrix size (inversion speed up)
- for AIRS: 2378 channels -> 250 nodes

$$\tilde{y}^m = \left(A^T S_e^{-1} A\right)^{-1} A S_e^{-1} y^m$$

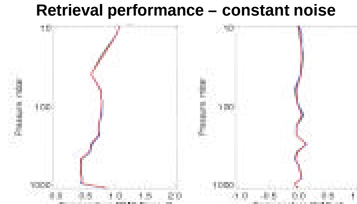
$$\tilde{S}_e^{-1} = A^T S_e^{-1} A$$

$$dx_{n+1} = \left(\tilde{K}_n^T \tilde{S}_e^{-1}\tilde{K}_n + S_x^{-1}\right)\tilde{K}_n^T\tilde{S}_e^{-1}\left[\left(\tilde{y}_n - \tilde{y}^m\right) + \tilde{K}_n dx_n\right]^{**}$$

**Equivalent to

$$dx_{n+1} = \left(K_n^T S_e^{-1} K_n + S_x^{-1}\right) K_n^T S_e^{-1}\left[\left(AHy_n - \tilde{y}^m\right) + K_n dx_n\right]$$

Retrieval performance – constant noise



•Need strategy for handling input dependent noise
- Scene temperature dependence (clear/cloudy)
  - – worse in SW band
- Cloud clearing noise amplification

•H-transformation not overly sensitive to noise
- For clear retrievals: sufficient to update noise covariance regionally